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Computational Imaging in Demanding Conditions

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Final Report

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In this project, we addressed some of the most challenging, yet seldom studied, open problems in image and video enhancement of interest to the Air Force; namely, the removal of disturbances due to demanding physical and environmental conditions. We considered degradations of interest that can be caused by a number of different physical phenomena (often occurring simultaneously) which are commonly encountered in practice.

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Final Report

AFOSR Grant FA9550-11-1-0227

"Computational Imaging in Demanding Conditions"

Peyman Milanfar, Principal Investigator
University of California, Santa Cruz, 95064

Summary:

In this project, we addressed some of the most challenging, yet seldom studied, open problems in image and video enhancement of interest to the Air Force; namely, the removal of disturbances due to demanding physical and environmental conditions. We considered degradations of interest that can be caused by a number of different physical phenomena (often occurring simultaneously) which are commonly encountered in practice. Such degradations include

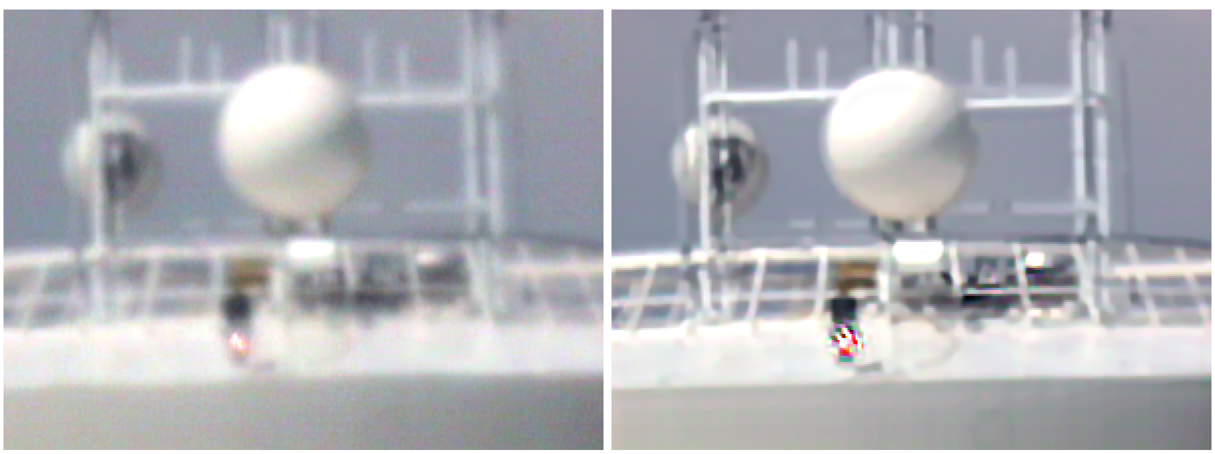
- air turbulence, resulting in pictures which suffer from random, spatially varying, blur,
- complex motion blur due to the non-stationarity of the imaging platform or the objects being imaged, resulting in pictures with highly variable blur characteristics, and
- non-ideal lighting and depth-of-focus conditions, resulting in images containing variable blur and significant levels of noise.

To address these problems, we proposed a novel adaptive framework. Specifically, in the case when multiple images are available (such as turbulence imaging), we automatically select isoplanatically blurred regions (i.e., those blurred with short-support point-spread functions,) which can approximately be viewed as space-invariant. From these a sharp image can be estimated through adaptive non-parametric fusion, followed by deconvolution. Experiments proved that this method could significantly reduce the effect of turbulence in the acquired imagery. More generally, a special case of this technique is also applicable when only a single image is available, and hence the general idea is applicable to the other scenarios as well. Finally, although spatial deblurring is relatively well-understood by assuming that the blur kernel is shift-invariant, spatially varying motion blur is not so when we attempt to deconvolve this motion blur on a frame-by-frame basis: this is because, in general, videos include complex, multi-layer transitions. Indeed, we face an exceedingly difficult problem in motion deblurring of a single frame when the scene contains multiple motions or occlusions. Instead of deblurring video frames individually, a fully 3-D deblurring method is proposed here. Most importantly, due

to its inherent locally adaptive nature, the proposed approach is capable of automatically deblurring the parts of the sequence which are motion blurred, without segmentation, and without adversely affecting the rest of the spatiotemporal domain where such blur is not present.

Detailed Accomplishments:

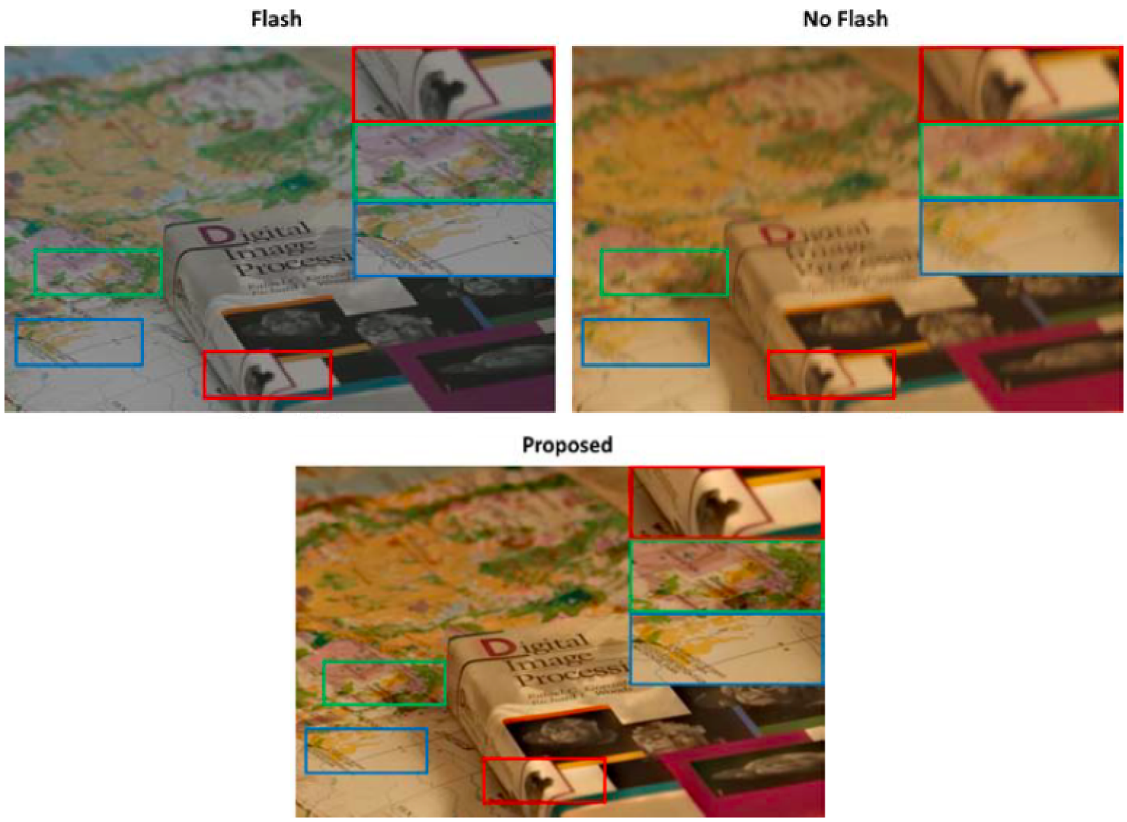
- ### Removing Atmospheric Turbulence via Space-Invariant Deconvolution:
  - To correct geometric distortion and reduce space and time-varying blur, a new approach is proposed capable of restoring a single high-quality image from a given image sequence distorted by atmospheric turbulence. This approach reduces the space and time-varying deblurring problem to a shift invariant one. It first registers each frame to suppress geometric deformation through B-spline-based nonrigid registration. Next, a temporal regression process is carried out to produce an image from the registered frames, which can be viewed as being convolved with a space invariant near-diffraction-limited blur. Finally, a blind deconvolution algorithm is implemented to deblur the fused image, generating a final output. Experiments using real data illustrate that this approach can effectively alleviate blur and distortions, recover details of the scene, and significantly improve visual quality
  - Also see related talk , Project page , Software package



- ### Estimating Spatially Varying Defocus Blur from A Single Image
  - Estimating the amount of blur in a given image is important for computer vision applications. More specifically, the spatially varying defocus point-spread-functions (PSFs) over an image reveal geometric information of the scene, and their estimate can also be used to recover an all-in-focus image. A

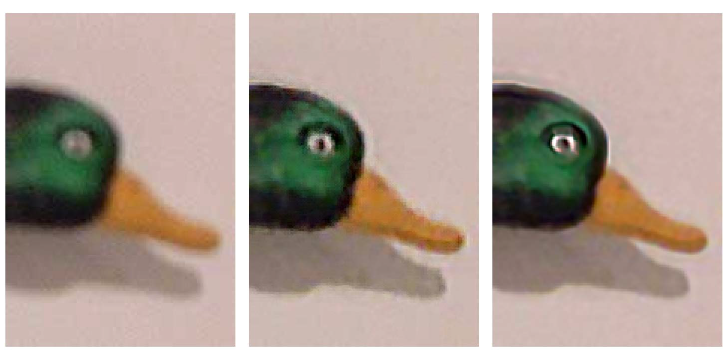
PSF for a defocus blur can be specified by a single parameter indicating its scale. Most existing algorithms can only select an optimal blur from a finite set of candidate PSFs for each pixel. Some of those methods require a coded aperture filter inserted in the camera. In this paper, we present an algorithm estimating a defocus scale map from a single image, which is applicable to conventional cameras. This method is capable of measuring the probability of local defocus scale in the continuous domain. It also takes smoothness and color edge information into consideration to generate a coherent blur map indicating the amount of blur at each pixel. Simulated and real data experiments illustrate excellent performance and its successful applications in foreground/background segmentation.

- Robust Flash Denoising/Deblurring by Iterative Guided Filtering
    - A practical problem addressed recently in computational photography is that of producing a good picture of a poorly lit scene. The consensus approach for solving this problem involves capturing two images and merging them. In particular, using a flash produces one (typically high signal-to-noise ratio [SNR]) image and turning off the flash produces a second (typically low SNR) image. In this article, we present a novel approach for merging two such images. Our method is a generalization of the guided filter approach of He et al., significantly improving its performance. In particular, we analyze the spectral behavior of the guided filter kernel using a matrix formulation, and introduce a novel iterative application of the guided filter. These iterations consist of two parts: a nonlinear anisotropic diffusion of the noisier image, and a nonlinear reaction-diffusion (residual) iteration of the less noisy one. The results of these two processes are combined in an unsupervised manner. We demonstrate that the proposed approach outperforms state-of-the-art methods for both flash/no-flash denoising, and deblurring.
    - Also see related [project page.]()

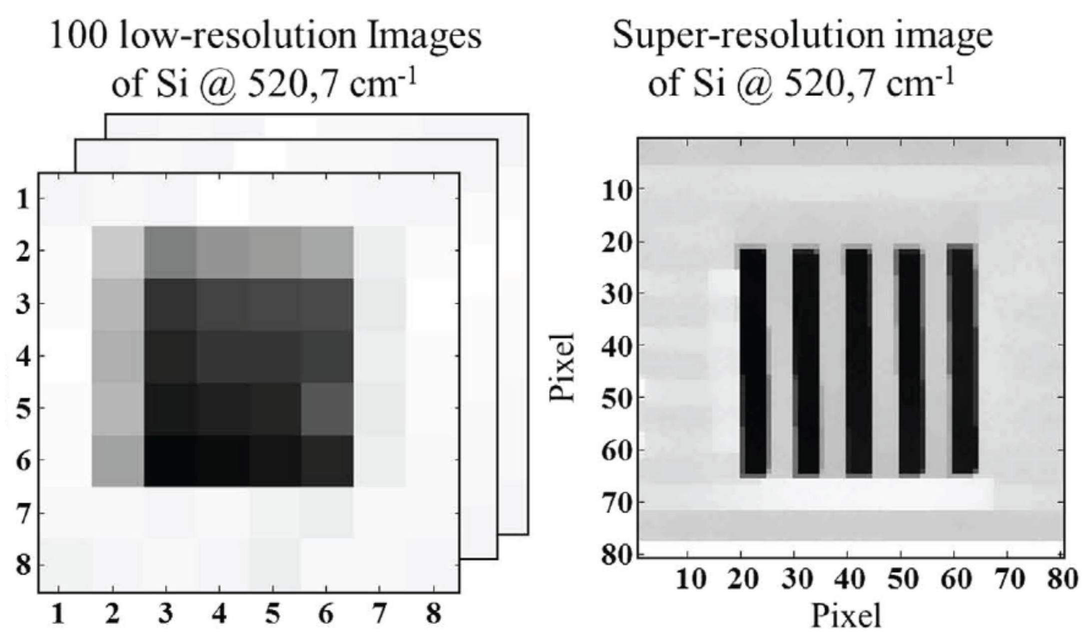


- Nonlocal Image Editing
  - We introduce a new image editing tool based on the spectrum of a global filter computed from image affinities. Recently, it has been shown that the global filter derived from a fully connected graph representing the image can be approximated using the Nyström extension. This filter is computed by approximating the leading eigenvectors of the filter. These orthonormal eigenfunctions are highly expressive of the coarse and fine details in the underlying image, where each eigenvector can be interpreted as one scale of a data-dependent multiscale image decomposition. In this filtering scheme, each eigenvalue can boost or suppress the corresponding signal component in each scale. Our analysis shows that the mapping of the eigenvalues by an appropriate polynomial function endows the filter with a number of important capabilities, such as edge-aware sharpening, denoising, tone manipulation, and abstraction, to name a few. Furthermore, the edits can be easily propagated across the image.
  - Also see related (Project Webpage)

- A General Framework for Regularized, Similarity-based Image Restoration
  - Any image can be represented as a function defined on a weighted graph, in which the underlying structure of the image is encoded in kernel similarity and associated Laplacian matrices. We developed an iterative graph-based framework for image restoration based on a new definition of the normalized graph Laplacian. We proposed a cost function, which consists of a new data fidelity term and regularization term derived from the specific definition of the normalized graph Laplacian. The normalizing coefficients used in the definition of the Laplacian and associated regularization term are obtained using fast symmetry preserving matrix balancing. This results in some desired spectral properties for the normalized Laplacian such as being symmetric, positive semidefinite, and returning zero vector when applied to a constant image. The proposed approach is general in the sense that we have shown its effectiveness for different restoration problems, including deblurring, denoising, and sharpening. Experimental results verify the effectiveness of the proposed algorithm on both synthetic and real examples.



- Pushing back the limits of Raman imaging by coupling super-resolution and chemometrics for aerosols characterization
    - The increasing interest in nanoscience in many research fields like physics, chemistry, and biology, including the environmental fate of the produced nano-objects, requires instrumental improvements to address the sub-micrometric analysis challenges. The originality of our approach is to use both the super-resolution concept and multivariate curve resolution (MCR-ALS) algorithm in confocal Raman imaging to surmount its instrumental limits and to characterize chemical components of atmospheric aerosols at the level of the individual particles. We demonstrate the possibility to go beyond the diffraction limit with this algorithmic approach. Indeed, the spatial resolution is improved by 65% to achieve 200 nm for the considered far-field spectrophotometer. A multivariate curve resolution method is then coupled with super-resolution in order to explore the heterogeneous structure of submicron particles for describing physical and chemical processes that may occur in the atmosphere. The proposed methodology provides new tools for sub-micron characterization of heterogeneous samples using far-field (i.e. conventional) Raman imaging spectrometer.



Additional Synergistic Activities and Accomplishments

- Distinguished Lecturer, IEEE Signal Processing Society
- Elected Fellow of the IEEE
- Supported and Graduated 5 Ph.D. Students, 2 M.S. Students
- Presented many plenary and keynote speeches, including:
    - (2015) *Plenary*, International Conference on Multimedia and Exposition, Torino
    - (2015) *Keynote*, SPIE Conference on Digital Image Processing, San Francisco
    - (2014) *Keynote*, Workshop on Co-design of hybrid imaging systems, Paris
    - (2014) *Plenary*, SPIE Optics and Photonics Symposium, San Diego
    - (2014) *Plenary*, Technion's TCE Symposium, Haifa
    - (2013) *Plenary*, Picture Coding Symposium
    - (2012) *Plenary*, Mathematics and Image Analysis Conference, Paris
    - (2010) *Keynote*, Pacific Rim Symp. on Image and Video Technology, Singapore

1.

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Final Report

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Peyman Milanfar

Program Manager

The AFOSR Program Manager currently assigned to the award

Arje Nachman

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Abstract

In this project, we addressed some of the most challenging, yet seldom studied, open problems in image and video enhancement of interest to the Air Force; namely, the removal of disturbances due to demanding physical and environmental conditions. We considered degradations of interest that can be caused by a number of different physical phenomena (often occurring simultaneously) which are commonly encountered in practice.

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Laboratory Task Manager

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Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
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Equipment/Facilities			
Supplies			
Total			

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